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Basinwide Considerations for Water Quality Management: Importance of Phosphorus Retention by Reservoirs

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Purpose

Reservoirs are designed and operated to control the flow of rivers to achieve flood control, water storage, power generation, irrigation, navigation, and other beneficial uses. From a water control or water quantity standpoint, reservoirs within the same drainage basin are often viewed as an integrated system to be optimized to achieve authorized reservoir uses and basinwide water control objectives. While methods for accomplishing this are well established, similar basinwide considerations for water quality are less common.

This technical note provides a theoretical basis for implementing basinwide water quality management by considering the water quality influences of reservoirs on regulated rivers, specifically, the retention of phosphorus.

Background

Free-flowing rivers are viewed as environmental continua along which geomorphic features, flow regime, material budgets, and the structure of biotic communities change in ecologically significant ways with increasing stream order (Vannote and others 1980). In general, headwater streams (stream order 1-3) experience low but seasonally variable flows, receive much of their organic carbon from terrestrial sources and, assuming minimal anthropogenic inputs, are low in suspended sediments and dissolved nutrients. Medium-sized streams and rivers (stream order 4-6) exhibit moderate flow rates with relatively large seasonal variations, high nutrient availability, high autochthonous production, and diverse biotic communities. Large rivers (stream order > 6) transport large nutrient and suspended sediment loads, have moderate to low biotic diversity, and exhibit moderate autochthonous production.

Dams interrupt this continuum by creating a series of alternating lotic and lentic reaches or a series of discontinuities resulting in longitudinal shifts in riverine characteristics (Ward and Stanford 1983). These shifts, which can be either negative (upstream) or positive (downstream), apply to physical and chemical characteristics, as well as to attributes of biotic communities. The degree of longitudinal shift may be conceptually quantified as a displacement or discontinuity distance measured as an absolute distance or as a change in stream order. Differences in the expected magnitude or intensity of a parameter may also be influenced positively or negatively

by the presence of a dam. For rivers with multiple reservoirs, discontinuity distances and changes in parameter intensity may be cumulative and difficult to quantify in absolute terms (Ward and Stanford 1983).

One well-documented impact of dams on river continua is the reduction in phosphorus concentrations due to uptake by phytoplankton and increased sedimentation (Kennedy, Thornton, and Ford 1985; Kennedy and Walker 1990; Kimmel, Lind, and Paulson 1990; Søballe and others 1992). The magnitude of such reductions, which would result in lowered nutrient levels in releases to downstream river reaches and reservoirs, is influenced by characteristics of the reservoir and the manner in which it is operated (Kennedy, Thornton, and Ford 1985). For instance, Štěpánek (1980) suggested that phosphorus retention may be influenced by reservoir surface area and mean depth, and phosphorus supply.

Straškraba and others (1995) and Wilhelmus, Bernhardt, and Neuman (1978, cited in Straškraba and others 1995) computed the degree of retention of total phosphorus for selected Czech reservoirs and orthophosphorus for German reservoirs, respectively, and evaluated relationships between phosphorus retention and water retention. Phosphorus retention values were low at low values of water retention but reached "saturation" levels with relatively modest increases in water retention. Based on these considerations, Straškraba and others (1995) suggested that reservoir managers could exert control over phosphorus retention at reservoirs with low water retention values (< 50-75 days), but that at higher values, changes in water retention time would have little effect on the percent phosphorus retention.

If similar relationships are demonstrable for Corps of Engineers reservoirs, manipulation of water retention time offers a potentially important tool for water quality managers. Benefits may also accrue at the basin level for watersheds with multiple or cascading reservoirs (Štěpánek 1980, Straškraba 1994b). This technical note describes methods for computing phosphorus and water retention time, and assessing their relationship for Corps reservoirs.

Methods

Water retention

Water retention time (R_T, commonly expressed in days or years), or the theoretical hydraulic residence time of a parcel of water in a reservoir, is computed as

$$R_T = V/Q \tag{1}$$

where

V = reservoir volume (L^3)
Q = reservoir discharge rate (L^3/T)

Since most reservoirs are operated for water storage, there is often a lag between water inflow and water discharge. Because of this, different values of R_T will be obtained if reservoir inflow

or discharge rate is used in the calculation. While such differences are of limnological interest, the latter value is used here to retain the convention established for natural lakes.

Phosphorus retention

Phosphorus retention (R_P) is computed from estimates of phosphorus input and output according to simple mass balance considerations (Dillon and Rigler 1975), as shown below.

$$R_P = (P_{in} - P_{out}) / P_{in} \tag{2}$$

where

P_{in} = phosphorus mass loading (M/T)
P_{out} = phosphorus mass discharge (M/T)

Storage of phosphorus in the water column and the effects of internal loading (e.g., release of phosphorus from sediments), while potentially influencing the value of P_{out}, are not explicitly addressed in the computation.

Corps-wide assessment

Relationships between R_T and R_P were assessed using data from two sources. A Corps-wide assessment of the frequency distribution of R_T values was based on average annual pool volumes and discharge rates for 204 Corps reservoir projects included in a tailwater and reservoir water quality database maintained by the U.S. Army Engineer Waterways Experiment Station. Values of R_P for 26 of the Corps reservoirs were based on annual mean inflow and discharge total phosphorus concentrations reported by Walker (1985) (Table 1). The proportionality of inflow soluble reactive or orthophosphorus concentration to inflow total phosphorus concentration was also obtained from Walker (1985). Areal phosphorus loads (grams/square meter/year) were based on annual mass load (P_{in}) and average annual pool area.

Categorical determinations of operational characteristics (surface, bottom, or mixed withdrawal) for the 26 reservoirs were based on the depths of water intake structures relative to the average total depth of the reservoir and the distribution of release volumes between structures. Reservoirs for which withdrawals were nearly equally distributed between surface or bottom, or which utilized withdrawal structures located at mid-depth, were categorized as exhibiting mixed withdrawal characteristics. No attempt was made to interpret the potential effects of stratification, flow, or structural design on actual withdrawal patterns.

Reservoirs were also categorized as to design strategy based on their location within the watershed relative to stream or river order. Reservoirs on low-order streams were categorized as tributary reservoirs while those located on middle- or high-order streams or rivers, were determined to be mainstem reservoirs. Run-of-river reservoirs are those located on the downstream reaches of large rivers from which they receive a majority of their inflow. It should be noted that this categorization differs from that of Kimmel and Groeger (1984), who defined tributary, mainstem, and run-of-river reservoirs based on R_T.

Table 1. Characteristics of Selected Corps Reservoirs (based on data from Walker 1985)						
Reservoir	River	Type	Operation	P_L g/m^2/year	R_T days	R_P percent
Atwood	Indian	Tributary	Surface	1.3	110	69.1
Baldhill	Sheyenne	Mainstem	Bottom	2.3	179	24.1
Bankhead	Black Warrior	Run-of-river	Bottom	15.8	14	18.7
Barkley	Cumberland	Run-of-river	Mixed	28.7	8	6.7
Barren River	Barren	Tributary	Bottom	2.8	58	14.9
Beaver	White	Mainstem	Mixed	1.2	349	73.7
Beltzville	Pohopoco	Tributary	Surface	0.7	89	18.5
Berlin	Mahoning	Tributary	Mixed	6.0	82	78.1
Bull Shoals	White	Mainstem	Mixed	1.5	215	63.0
Carlyle	Kaskaskia	Mainstem	Mixed	5.8	45	39.7
Charles Mill	Black Fork	Tributary	Surface	8.4	13	10.9
Delaware	Olentangy	Tributary	Surface	23.8	13	35.4
Dillon	Licking	Mainstem	Surface	23.8	9	24.1
Dworshak	Clearwater	Tributary	Mixed	1.9	220	14.9
Holt	Black Warrior	Run-of-river	Bottom	30.6	5	12.9
J. Percy Priest	Stones	Tributary	Mixed	5.6	76	27.6
John Redmond	Neosho	Tributary	Mixed	17.3	20	53.2
J. Strom Thurmond	Savannah	Mainstem	Bottom	1.2	160	81.7
Milford	Republican	Mainstem	Bottom	3.7	400	88.5
Mississinewa	Mississinewa	Tributary	Mixed	27.6	33	61.1
Pleasant Hill	Clear Fork	Tributary	Surface	3.9	30	2.1
Richard B. Russell	Savannah	Mainstem	Bottom	0.9	108	36.1
Sakakawea	Missouri	Mainstem	Bottom	7.2	325	92.4
Shelbyville	Kaskaskia	Mainstem	Mixed	5.2	73	39.8
Table Rock	White	Mainstem	Mixed	0.9	160	32.4
Tenkiller Ferry	Illinois	Tributary	Mixed	4.3	124	48.7

Results

Operational characteristics and design strategies for the 26 reservoirs for which phosphorus budget information was available (Table 1) were representative of reservoirs Corps-wide. Mainstem and tributary reservoirs were nearly equally distributed and accounted for 88 percent of the reservoirs. Most (46 percent) of the reservoirs exhibited mixed withdrawal characteristics, mainly due to the mid-depth location of the withdrawal structure. No clear trends were observed in relationships between operational characteristics and mean depth or reservoir design strategy.

The R_T values computed for 204 Corps reservoirs varied widely and exhibited a strongly skewed distribution (Figure 1a). Approximately 50 percent of the projects have R_T values less than 90 days; 34 percent have R_T values less than 30 days. Less than 15 percent of Corps reservoirs have R_T values of 1 year or more. A similar frequency distribution of R_T values was observed for the 26 Corps reservoirs for which phosphorus budget information was available (Figure 1b). Lacking were reservoirs with R_T values in excess of 400 days.

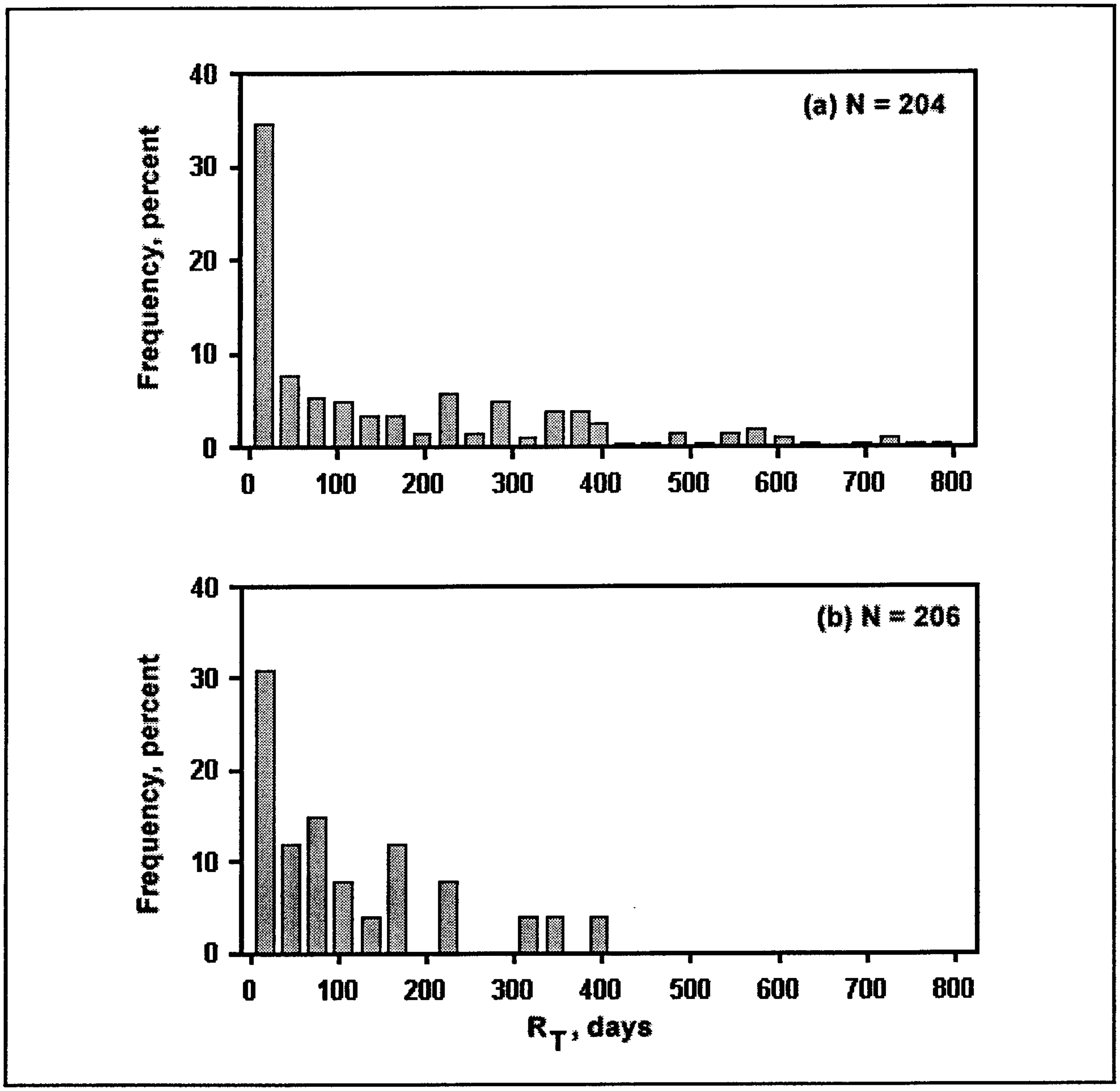

Figure 1. Frequency distribution of R_T values for 204 Corps reservoirs (panel a) and for 26 Corps reservoirs for which phosphorus budget information was available (panel b)

While variable within categories (Table 1), a clear trend was observed between R_T values and reservoir design strategy. Largest R_T values (median = 160 days) were associated with mainstem reservoirs, while short retention times (median = 8 days) were observed for run-of-river reservoirs. A median R_T value of 67 days was observed for tributary reservoirs.

The relationship between R_P and R_T for Corps reservoirs (Figure 2) was highly variable and incompletely described by equations developed by Straškraba and others (1995) and Wilhelmus, Bernhardt, and Neuman (1978, cited in Straškraba and others 1995). Most notable was the observation that several reservoirs with $R_T > 90$ days exhibited relatively low phosphorus retention ($R_P < 50$ percent). This variability was not accounted for by differences in reservoir

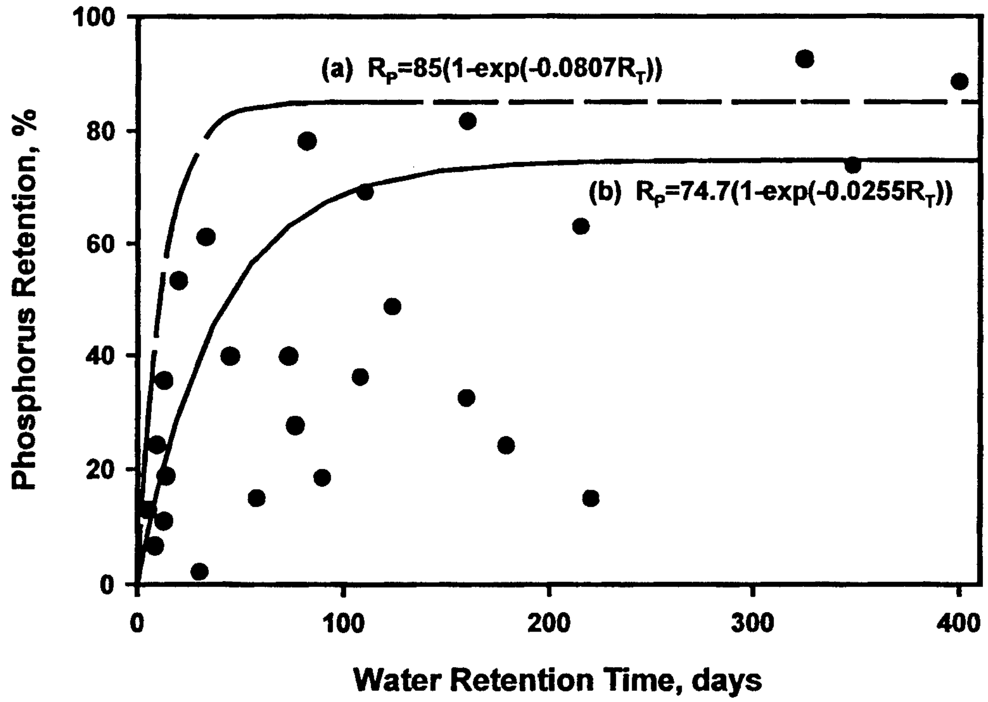

Figure 2. Relationship between R_P and R_T values for selected Corps reservoirs (closed circles). Curves represent relationships observed for (a) German reservoirs (Wilhelmus and others 1978) and (b) Czech reservoirs (Straškraba and others 1995)

design strategy (Figure 3a) nor operational characteristics (Figure 3b). Since increases in the relative proportion of the particulate fraction of phosphorus loads would increase the potential for losses due to sedimentation, differences in inflow (F_{OT}) were expected to influence R_P. However, such influences on the relationship between R_P and R_T were not apparent (Figure 4).

Differences in areal phosphorus load accounted for much of the variability in the relationship between R_P and R_T for Corps reservoirs (Figure 5). Reservoirs with high areal phosphorus loads (>15 g/m^2/year) conformed to relationships reported by Straškraba and others (1995) and Wilhelmus, Bernhardt, and Neuman (1978, cited in Straškraba and others 1995) in that R_P increased markedly with modest increases in R_T. Reservoirs with relatively low areal phosphorus loading rates (<5 g/m^2/year) exhibited a lower rate of change in R_P in response to increases in R_T. Intermediate responses were observed for reservoirs with areal phosphorus loading rates in the range of 5 to 15 g/m^2/year.

Discussion

Reservoirs are frequently viewed as imposing negative impacts on the aquatic environment (Avakyan and Iakovleva 1998). However, as engineered features common on the current landscape, they offer a potential management tool if relationships between reservoir operation and water quality influences can be understood (Straškraba 1994a). Knowledge of such

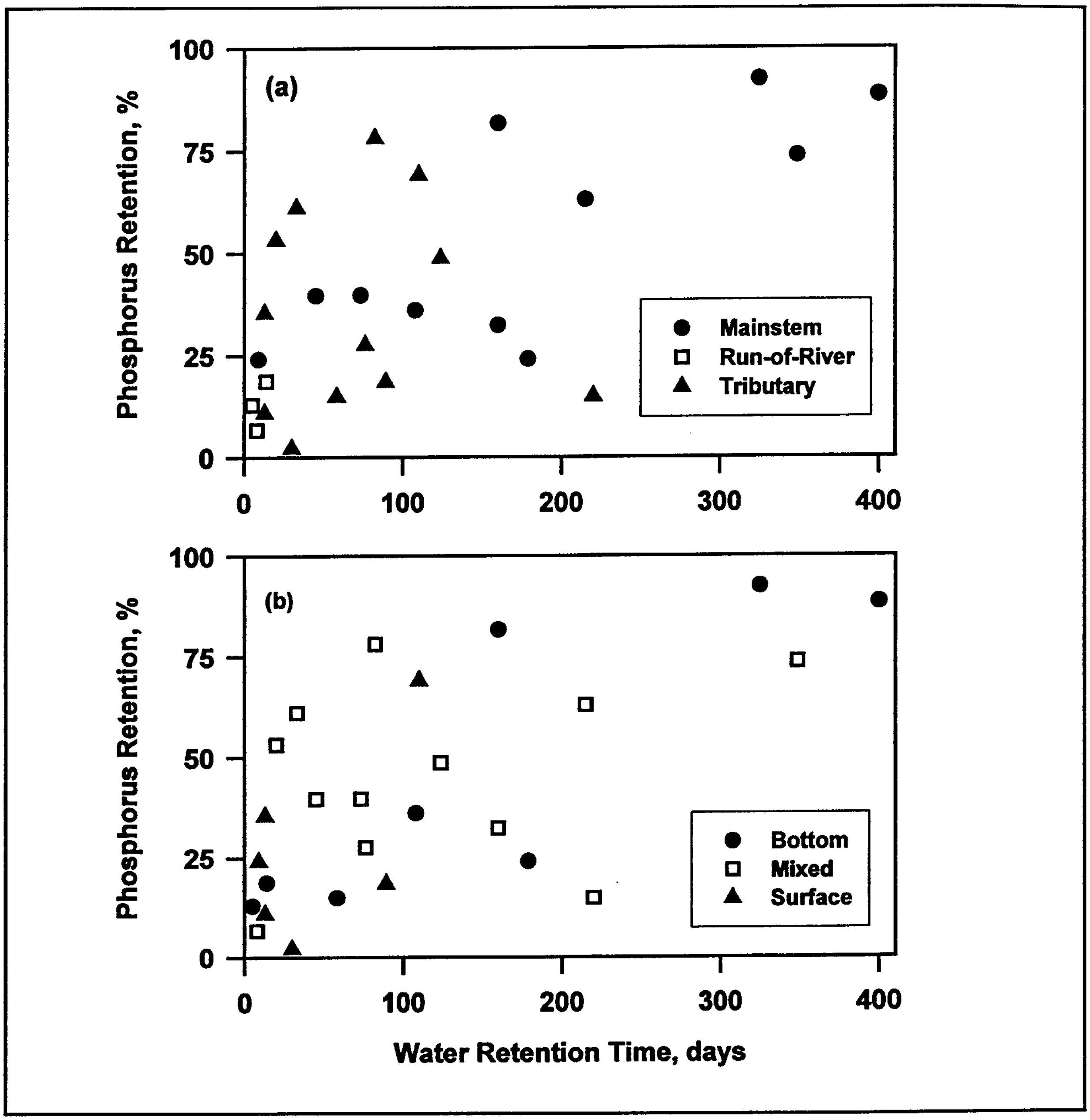

Figure 3. Relationship between R_P and R_T values for selected Corps reservoirs relative to reservoir design strategy (upper panel) and operational characteristics (lower panel) (see symbol legends)

relationships—which may have both local importance (that is, at or below a single reservoir) and basinwide significance—allows a potentially efficient means to manage potential impacts while sustaining benefits from original reservoir uses.

The importance of the influence of R_T on reservoir water quality is clear. The rate at which reservoirs are flushed modifies thermal structure and the potential for mixing (Kennedy, Thornton, and Ford 1985; Straškraba 1994b); affects changes in material budgets (Štěpánek 1980, Straškraba and others 1995) and light attenuation (Townsend, Luong-Van, and Boland

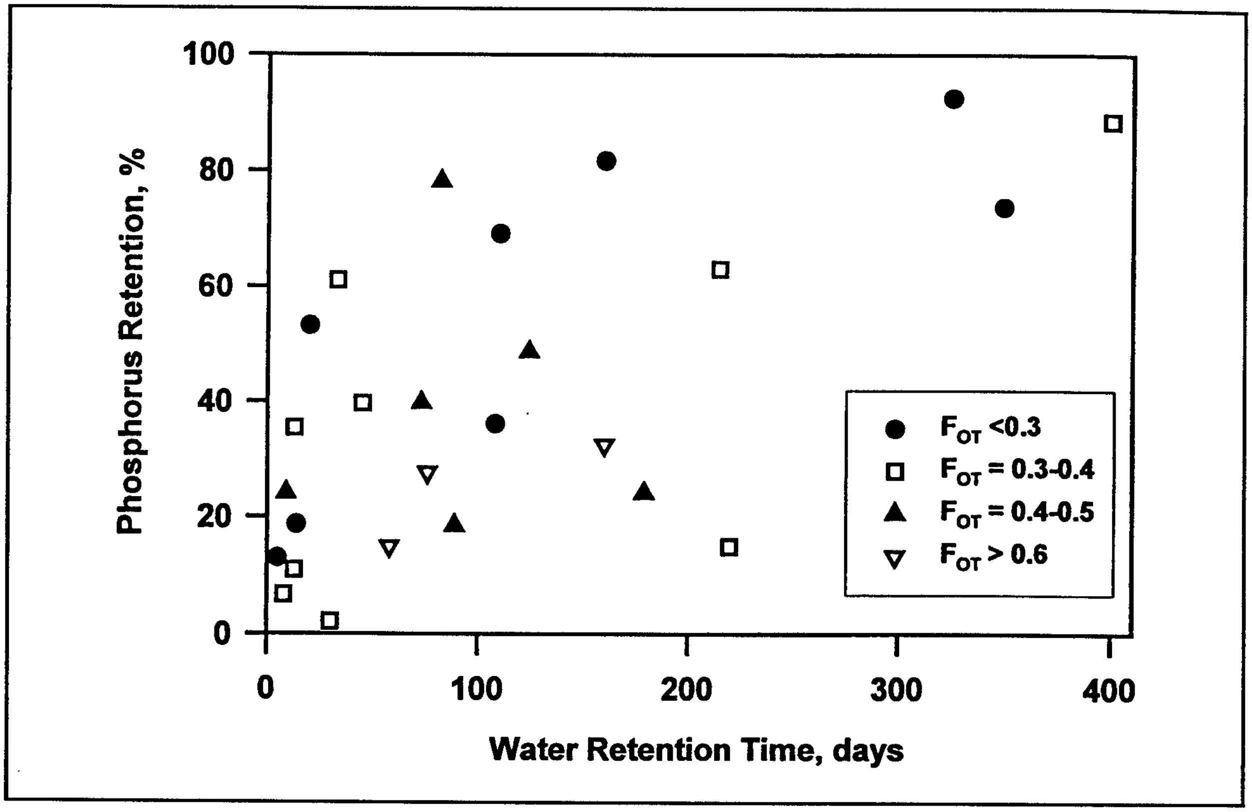

Figure 4. Relationship between R_P and R_T values for selected Corps reservoirs relative to inflow F_{OT} (see symbol legend)

1996); and influences algal transport and abundance (Søballe and Bachmann 1984, Søballe and Kimmel 1987). Demonstrated here for Corps reservoirs is the importance of the relationship involving R_T, R_P, and areal phosphorus loading rate. For reservoirs with high areal phosphorus loading and low values of R_T, R_P increases markedly with modest increases in R_T. At lower areal phosphorus loads, responses of R_P to changes in R_T are less dramatic.

While commonly computed as an average annual value, R_T values based on water balance data for shorter periods of time often exhibit marked seasonal variation due to changes in hydrology and reservoir operation. West Point Lake, Georgia, provides an example of temporal variability in hydrologic conditions (Figure 6). Pool elevation increases in spring coincident with elevated spring inflows, declines in late summer and early fall, and increases again in late fall with increasing inflows. R_T values, computed based on average monthly outflows and pool elevations (volume), range from less than 30 days in early spring to over 100 days in early summer. The annual areal phosphorus load to the reservoir for water year 1991 was 7.2 g/m^2/year (Emmerth and Bayne 1996). Using the estimated relationship between R_P and R_T for reservoirs with moderate areal phosphorus loads (that is, 5 to 15 g/m^2/year; Figure 5), approximate values of R_P for the observed range in R_T would be 23 and 58 percent, respectively. When viewed in a basinwide context, phosphorus loads to the downstream river reach or to the next downstream reservoir could change by as much as 40 to 45 percent. Such changes in phosphorus load would clearly influence river or reservoir water quality.

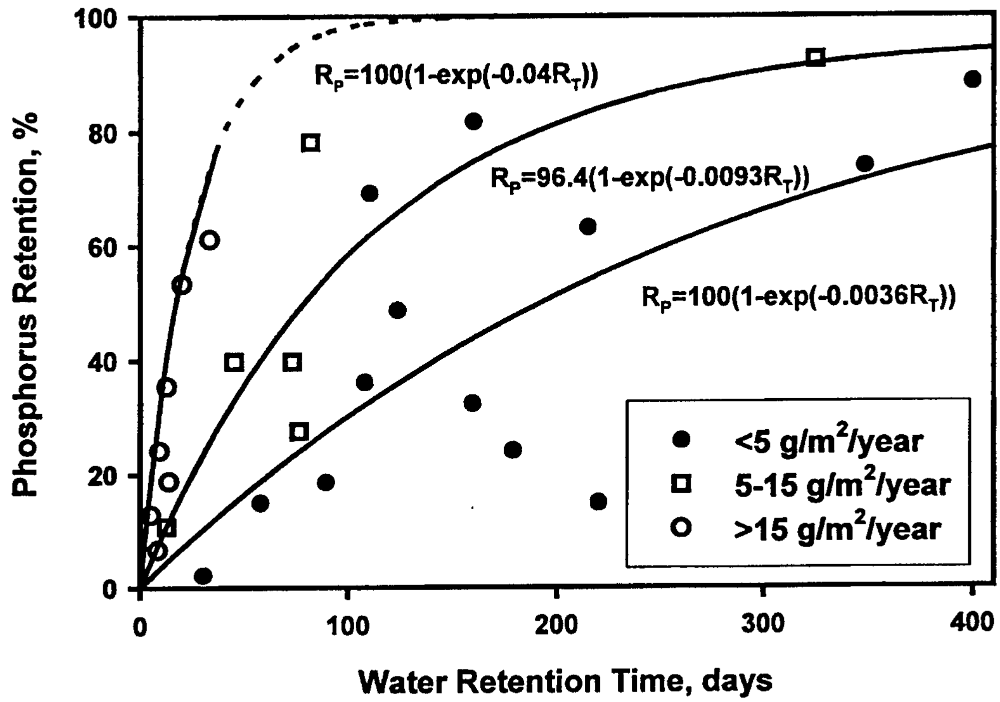

Figure 5. Relationship between R_P and R_T values for selected Corps reservoirs with differing areal phosphorus loads. Curves estimate relationships for each of three areal phosphorus loading categories

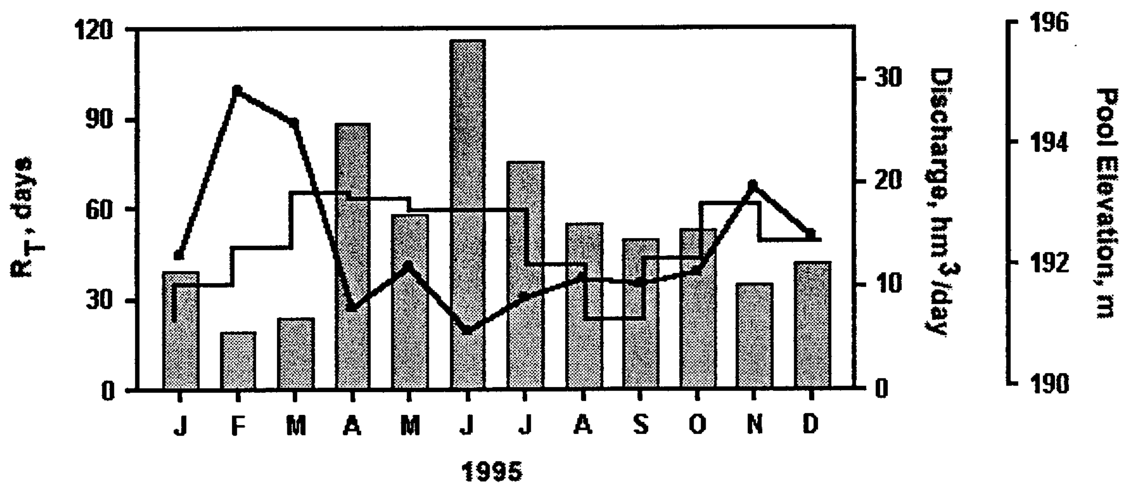

Figure 6. Monthly changes in R_T (vertical bar), discharge (line with closed circles), and pool elevation (stepped line) for West Point Lake, Georgia

Selective manipulation of R_T within the limits of water control requirements provides a possible means to modify R_P and, thus, basinwide phosphorus budgets. Rule or guide curves describe designed seasonal changes in reservoir surface elevation or volume required to accomplish water control goals. Changes in R_T are dictated by these curves and hydrologic inputs. If changes to a reservoir's guide curve result in a water quality benefit (for example, reduced downstream phosphorus loads due to increased R_P at an upstream reservoir) while still allowing water control goals to be met, then environmental benefits can be realized at minimal expense. Examples of possible changes to guide curves include increasing average annual reservoir volume and modifying the timing or rate at which changes in reservoir volume occur (for example, delaying reductions in reservoir volume following flood events).

Reservoir managers can identify management opportunities by reviewing water control plans to determine if there is sufficient latitude to allow operational modifications that will result in environmental benefit. With regard to basinwide phosphorus budgets, rapidly flushed reservoirs (that is, low values for R_T) may offer the greatest management opportunities, particularly if they receive relatively high phosphorus loads. Such reservoirs could provide a focal point for basinwide management initiatives.

Conclusions

Basinwide water quality management can be enhanced by understanding relationships between operation and water quality, on both local and basinwide scales. In drainage basins with multiple reservoirs, operational decisions based on both water quantity and quality should involve identification of those reservoirs whose characteristics offer management alternatives. In the case of phosphorus retention (R_P), those reservoirs for which marked changes in R_P occur with modest changes in water retention time should be considered for their potential to act as management points within the basin.

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